**Final Report**

AFOSR Project:

# Adaptive Models and Fusion Algorithms for Information Exploitation

Syracuse University
Syracuse, NY 13244

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Principal Investigator: Prof. Pramod K. Varshney
Department of EECS, Syracuse University

Co-Investigators: Prof. Chilukuri K. Mohan
Department of EECS, Syracuse University

Prof. Kishan G. Mehrotra
Department of EECS, Syracuse University

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Pramod K. Varshney

Chilukuri K. Mohan

Kishan G. Mehrotra

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**14. ABSTRACT**
The main aims for the project were to develop methodologies for managing and exploiting information available from multiple heterogeneous sensors/sources under limited sensing, computation and communication capabilities. Towards these goals, we conducted research along four directions, viz., source querying strategies, information fusion algorithms, learning algorithms to model the changing nature of data sources, and algorithms to exploit spatiotemporal relationships between different sources. We addressed realistic scenarios, with constraints on communication and computational resources, and characterized by time-varying and unpredictable changes in environments with spatially mobile entities. In many such problem scenarios, the information gathering and analysis efforts are complicated by the fact that data sources may be faulty and unreliable. This motivated addressing the tasks of situation assessment using asynchronous, heterogeneous and uncertain data sources. Results obtained have been documented in a number of technical publications.

**15. SUBJECT TERMS**
Information Fusion, Artificial Intelligence, Sensor Networks

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## 2. Objectives

Our research efforts addressed the tasks of situation assessment using asynchronous, heterogeneous and uncertain data sources. Methodologies were developed for managing and exploiting information available from multiple heterogeneous sensors/sources under limited sensing, computation and communication capabilities. This required progress towards four objectives:

- Strategies for effective data source querying;
- Algorithms for information fusion from multiple data sources;
- Algorithms for learning the changing nature of data sources; and
- Algorithms to exploit spatiotemporal relationships between different data sources.

## 3. Research Efforts *(200 word summary)*

In this project, considerable efforts were expended on problem analysis, problem formulation, scenario development, algorithm design, and performance evaluation, making continuous progress towards the four objectives listed above. Data source querying was formulated as a sensor selection problem for the scenario of target tracking in sensor networks. The joint recursive one-step-ahead *Posterior* Cramér-Rao Lower Bound (PCRLB) was introduced as the criterion for sensor selection to optimize tracking accuracy. Further, conditional PCRLB that is dependent on the past tracking data was explored in a mathematically well-founded approach. Learning algorithms based on neural networks and information fusion algorithms based on bootstrap approximate likelihood were developed to model the changing characteristics of data sources, inter-source spatiotemporal relationships, as well as source-environment relationships for the scenario of field estimation in sensor networks. In order to provide a context for the project objectives, the practical scenario of user movement in hazardous environments was thoroughly investigated. A centralized hierarchical path planning algorithm that is computationally very efficient was proposed for risk minimization in hazardous environments. In addition, distributed algorithms were designed for in-network path planning that enables a distributed sensor network navigation service to be implemented in hazardous environments that are dynamically evolving.

## 4. Summary of Accomplishments/New Findings

### Query Strategies

Effective query strategies can help information analysts improve situation assessment in military scenarios by determining which data sources to query and when, as well as what queries to pose to various data sources. In this project, we focused on a task that occurs frequently in military scenarios, i.e., target tracking in sensor networks, to study problem-specific query strategies. In this scenario, data sources are the sensors that perform the sensing task to generate noisy measurements and they are of dynamically evolving nature due to target motion. Thus, data source querying can be formulated as the sensor selection problem, where the task is to dynamically select and query a subset of sensors for their measurements over time to optimize tracking performance in terms of tracking accuracy. One new technical challenge in this context is that sensors to be queried have to be selected without the knowledge of future measurements.

We introduced the joint recursive one-step-ahead *Posterior* Cramér-Rao Lower Bound (PCRLB) as the criterion for sensor selection. This criterion considers not only the sensing accuracy of individual sensors (i.e., faulty data sources), but also sensor locations relative to target position and the posterior Probability Density Function (PDF) of the target state (i.e., situation awareness determined by the relevance of a data source to the current situation). We established a cost function for sensor selection based on the expected PCRLB, which is computed by a particle filter. Sensors that collectively minimize the cost function are selected for querying. Simulation results for both cases of quantized and unquantized sensor measurements show that our particle filter-based PCRLB method for sensor selection outperforms the nearest neighbor method, the entropy based method, as well as the EKF *posterior* CRLB driven method, in terms of tracking accuracy defined by mean square error (MSE). One interesting result we obtained is presented in Figure 1.

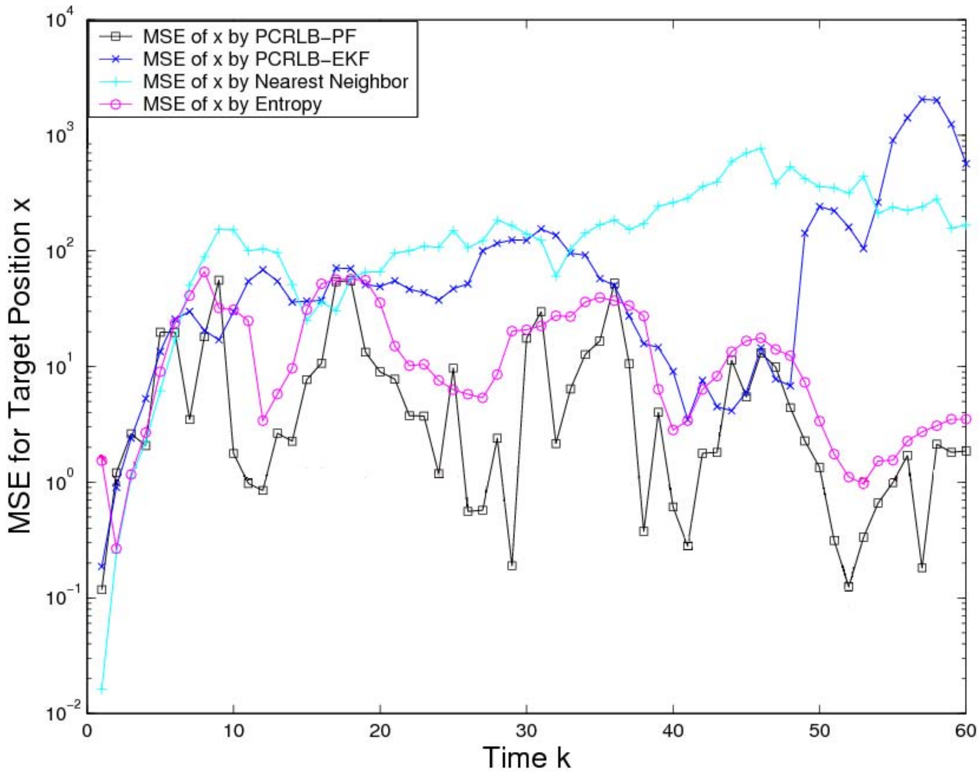


Figure 1: Comparison of posterior CRLB to MSEs for the x-coordinate of target position calculated using different sensor selection methods.

However, in the PCRLB based approaches developed thus far, the conventional unconditional PCRLB has been used to formulate a cost function. In an unconditional PCRLB, the Fisher Information Matrix (FIM) is derived by taking the expectation with respect to a joint distribution of the measurements and the target states up to the current time. As a result, the target track information is averaged out and the unconditional PCRLB becomes an offline bound, which is only determined by the system dynamic model, system measurement model and the prior knowledge regarding the target state at the initial time, and is thus independent of any specific realization of the target track. As a result, the unconditional PCRLB cannot reflect the target tracking performance for a particular track realization very faithfully. This is especially true when the uncertainty in state model (or equivalently the state process noise) is high and the prior knowledge regarding the target state at the initial time quickly becomes irrelevant as the target state evolves over time.

We proposed a conditional PCRLB based sensor selection approach that is dependent on past data and hence implicitly dependent on the target track up to the current time. The conditional PCRLB can provide a bound on the MSE of the target state estimate at a future time, based on the measurements up to the current time. Since the conditional PCRLB is a function of the past history of measurements, which contains the information of the current realization of the target track, a criterion based on it is expected to lead to much better solutions to the sensor selection problem than those based on the unconditional PCRLB. We performed both the mathematical derivation and the Monte Carlo approximation for this bound. Figure 2 shows one of the results we obtained.

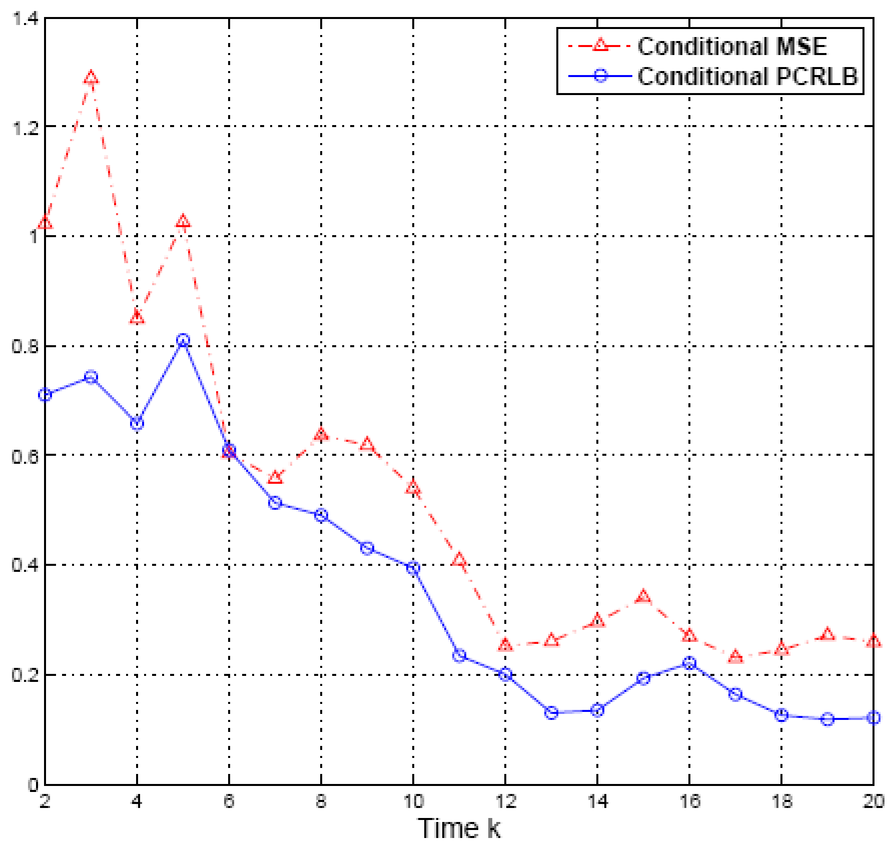


Figure 2: Plot of conditional posterior CRLB vs. conditional MSE.

The proposed bound can be used to address a variety of sensor management problems in sensor networks, as well as problems in which it is necessary to sequentially evaluate the performance limitations of a nonlinear recursive estimator.

## Learning and Information Fusion Algorithms

Information fusion involves drawing inferences from multiple uncertain data sources to obtain a more informed decision. Learning algorithms (such as neural network training algorithms or fuzzy classifier systems) can be used to derive new knowledge from prior knowledge and recently acquired data. In this project, we applied learning and data fusion algorithms to model the changing characteristics of data sources, inter-source spatiotemporal relationships, as well as source-environment relationships.

We focused the study on a common scenario in applications involving situational awareness: field estimation in sensor networks. In this scenario, sensor networks monitor spatially distributed processes such as plumes, fires, and movement of hazardous liquids or gases. Sensors (data sources) collect noisy samples of a physical parameter (e.g., temperature or gas concentration) and then deliver them to a fusion center over wireless channels. The fusion center estimates the physical field based on processing these noisy observations, distributed spatially (from multiple sensors in space) and temporally (multiple observations over time, from a single sensor).

We investigated the effects of imperfect channels (random errors and burst errors) on the estimation quality of the physical parameter of interest. To combat the effect of imperfect channels, we employed inherent spatial correlation among sensor observations among neighbors. Our approach is based on a novel application of a supervised local function learning algorithm that employs a Generalized Regression Neural Network (GRNN) to learn the spatial concentration function. An important advantage of our approach is that it does not require additional infrastructure or communication overhead. One of the important results obtained using this approach is shown in Figure 3.

We also proposed a new information fusion approach based on approximate likelihood. We first applied bootstrap sampling techniques to obtain the approximate likelihood function of the estimate obtained for the GRNN estimate. We then used maximum likelihood method to fuse the information of the direct observations and the observations estimated by the GRNN estimator. This approach can be applied to infer expected data source reports based on other correlated sources of its neighbors. If the sensor observation differs significantly from the inferred observation from the neighbors, the sensor is concluded to be faulty. Thus, the approach can also use estimation results to identify and mitigate the effects of the faulty data sources.

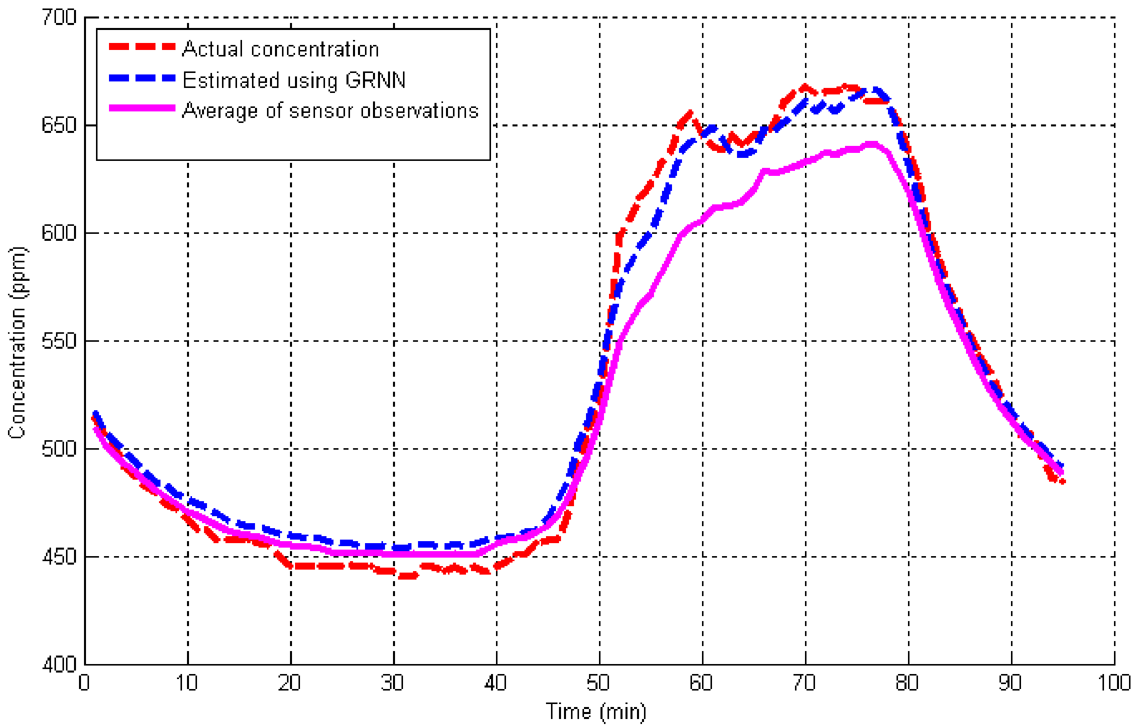

Figure 3: Actual concentration of gas and estimated concentration at a specified location

**Application Scenario Development**

Practical scenarios in mission-critical applications such as emergency evacuation, search-and-rescue, military deployment, strategy planning, and mission management provide contexts for our research efforts in this project. These scenarios often involve the movements of mobile users like personnel, robots, or vehicles in hazardous environments, which necessitates the development of new path planning and navigation algorithms.

We developed several path planning algorithms for evacuation and user movement in hazardous environments. In particular, we designed centralized algorithms for hierarchical path planning as well as distributed algorithms for in-network path planning. Our new contributions are briefly summarized in the following.

In centralized path planning problems, the computational time is of critical significance. We proposed a Hierarchical Path Planning Algorithm (HIPLA) for real time path planning in a central unit. The main idea of HIPLA is to significantly reduce the search space for path computation by searching in a high-level abstraction graph, whose nodes are associated with pre-computed risk estimates. The cumulative risk associated with all the nodes along a path determines the quality of a path. HIPLA is computationally very efficient and is readily applicable for path computation problems for large graphs of 10000 or more nodes in static and dynamic environments. Simulation results demonstrate that HIPLA guarantees near optimal solutions with much less computational effort when compared to two well known algorithms: shortest path algorithm (SPAH) and Dijkstra's algorithm with pruning (DP) for large node-weighted graphs.

We also designed a set of distributed algorithms for in-network path planning that enables a distributed sensor network navigation service. The service is able to guide the movements of users in hazardous environments that are dynamically evolving. Using actual geographic or virtual coordinates of sensors and based on a partial reversal method of directed acyclic graphs, our algorithms construct a global directed navigation graph in a localized fashion, where each source sensor is guaranteed to have at least one directed navigation path to one destination sensor. When the hazardous environment changes due to its dynamic nature, path re-planning does not need to reconfigure most of the directed links in the graph unaffected by the changes. Correctness of our algorithm is proved and a comprehensive performance evaluation in large-scale sensor networks (with 16384 sensors) via simulations demonstrates that the constructed navigation graph (e.g., shown in Figure 4) provides near-optimal navigation paths for users, successfully adapts to dynamic hazardous environments, and requires very low communication overhead for maintenance, when compared to other navigation graphs constructed by existing algorithms that use frequent or periodic flooding. Technical innovations of our algorithms lie in the successful exploitation of limited information to achieve global path planning in dynamic hazardous environments.

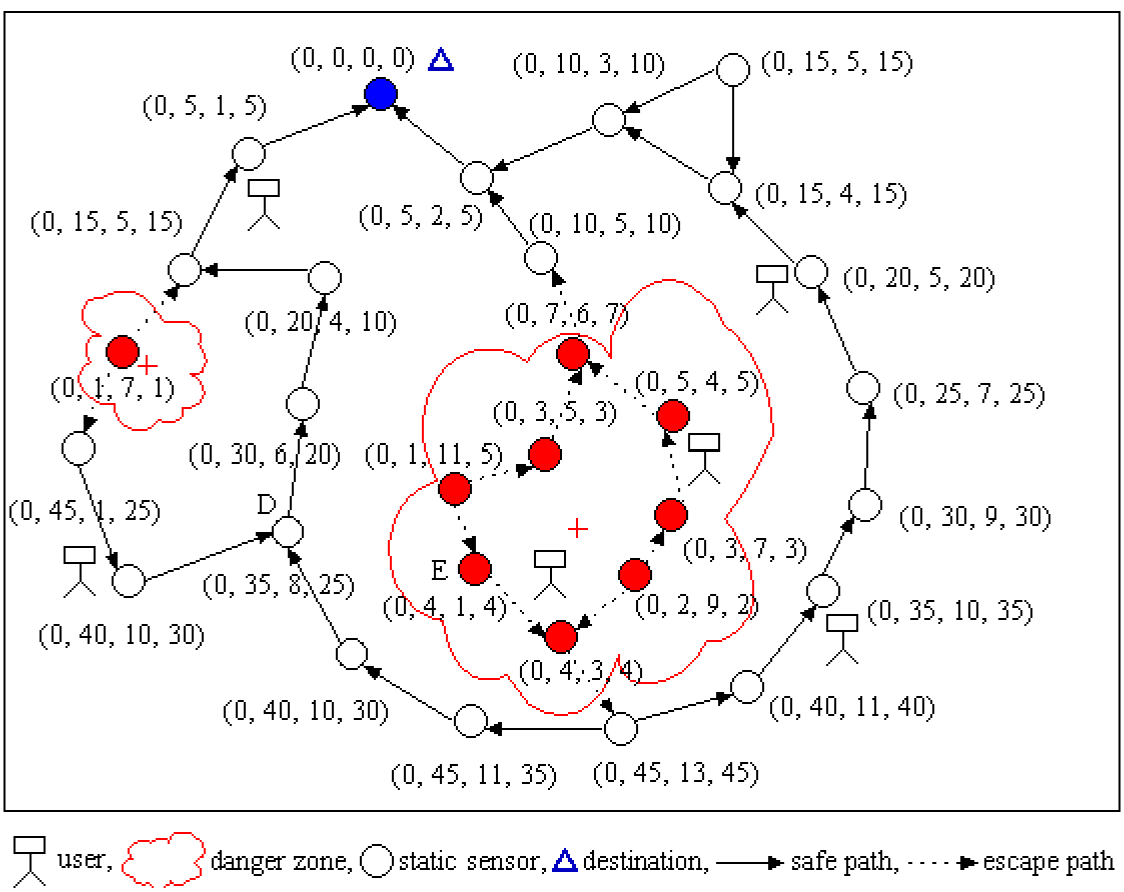


Figure 4: A sample scenario to demonstrate a directed navigation graph constructed by our distributed path planning algorithms.

## 5. Personnel Supported

- Prof. Pramod K. Varshney (PI)
- Prof. Chilukuri K. Mohan (co-PI)
- Prof. Kishan G. Mehrotra (co-PI)
- Dr. Ruixin Niu (Research Assistant Professor)
- Dr. Dazhi Chen (Postdoctoral research associate)
- Dr. Ramesh Rajagopalan (Ph.D. student, currently an Assistant Professor at the University of St. Thomas)
- Long Zuo (Ph.D. student)
- Priyadip Ray (Ph.D. student)
- Bhagavath Kumar (M.S. student, now employed at ESRI)
- Nikhil Padhye (Undergraduate student)

## 6. Publications

1. On Reliable Transport and Estimation of Spatio-temporal Events Using Wireless Sensor Networks (P. Ray, P. K. Varshney, and C. K. Mohan), *Proc. of the 40th Conference on Information Science and Systems*, Princeton, 2006.
2. Bandwidth-Efficient Target Tracking In Distributed Sensor Networks Using Particle Filters(Long Zuo, Kishan Mehrotra, Pramod Varshney, Chilukuri Mohan), *FUSION 2006,* Convitto della Calza, Florence, Italy, 10-13 July 2006
3. Data-aggregation techniques in sensor networks: A survey (R. Rajagopalan and P. K. Varshney), *IEEE Communications Surveys and Tutorials*, vol. 8, pp. 48-63, Fourth Quarter, 2006.
4. Posterior CRLB Based Sensor Selection for Target Tracking in Sensor Networks (L. Zuo, R. Niu, and P. K. Varshney), *Proc. of the IEEE 2007 International Conference on Acoustics, Speech, and Signal Processing*, Honolulu, Hawaii, 2007.
5. Temporal Uncertainty Reasoning Networks for Evidence Fusion with Applications to Object Detection and Tracking (C. K. Mohan, K. G. Mehrotra, P. K. Varshney, and J. Yang), *Information Fusion*, Vol. 8, PP. 281-294, 2007.
6. On demand geographic forwarding for data delivery in wireless sensor networks (D. Chen and P. K. Varshney), *Computer Communications*, vol. 30, pp. 2954-2967, Oct. 2007.
7. A Sensor Selection Approach for Target Tracking in Sensor Networks with Quantized Measurements (L. Zuo, R. Niu, and P. K. Varshney), *Proc. of the IEEE 2008 International Conference on Acoustics*, *Speech, and Signal Processing*, Las Vegas, Nevada, 2008.
8. EMOCA: An Evolutionary multi-objective crowding algorithm (R. Rajagopalan, C.K Mohan, K. Mehrotra and P. K. Varshney), *J. Intell. Syst.*, vol. 17, pp. 107-123, 2008.
9. Hierarchical Path Computation approach for large graphs (R. Rajagopalan, K. Mehrotra, C.K Mohan, and P. K. Varshney), *IEEE Trans. Aerosp. Electron. Syst*., vol. 44, pp. 427-440, Apr. 2008.
10. In-Network Path Planning for Distributed Sensor Network Navigation in Dynamic Environments (D. Chen, B. Kumar, C. Mohan, K. Mehrotra, and P. K. Varshney), *Proc. Of the Fifth IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (MASS)*, 2008.

11. Geographic routing in Wireless Ad Hoc Networks (D. Chen and P. K. Varshney), Book Chapter, *Guide to Wireless Ad Hoc Networks*, Springer, 2009.
12. Conditional Posterior Cramér-Rao Lower Bounds for Nonlinear Recursive Filtering (L. Zuo, R. Niu, and P. K. Varshney), *Proc. of the 12$^{th}$ International Conference on Information Fusion*, 2009.
13. Estimation of Spatially Distributed Processes in Wireless Sensor Networks with Random Packet Loss (P. Ray and P. K. Varshney), *IEEE Transactions on Wireless Communications*, pp. 3162-3171, June 2009.
14. Connectivity analysis of wireless sensor networks with regular topologies in the presence of channel fading (R. Rajagopalan and P. K. Varshney), to appear in *IEEE Trans. Wireless Communications*, pp. pp. 3475-3483, July 2009.
15. Distributed In-Network Path Planning for Sensor Networks Navigation in Dynamic Hazardous Environments (D. Chen, C. Mohan, K. Mehrotra, and P. K. Varshney), submitted to *Wiley Wireless Communications and Mobile Computing*, 2009.
16. Dynamic and Evolutionary Multi-objective Optimization for Sensor Selection in Sensor Networks for Target Tracking (N. Padhye, L. Zuo, C.K. Mohan, and P.K. Varshney), to appear in Proc. International Conference on Evolutionary Computation, Madeira (Portugal), Oct. 2009.

## 7. Interactions/Transitions

Cooperative Research Agreement with Army Research Laboratory in the area of heterogeneous sensor data fusion for personnel activity detection.

Cooperative Research Agreement with Oak Ridge National Laboratory in the area of detection and tracking of spatio-temporal phenomena.

Industry collaboration with several small businesses: a) Technical assist/Consulting with ANDRO Computational Solutions (POC Andy Drozd), with several SBIR projects in the areas of image registration and sensor fusion for missile tracking and recognition from AFRL and Missile Defense Agency; b) Technical assist with Digicomp Corp. (POC Om Gupta) with an STTR proposal to DARPA in sensor fusion and statistical decision theory for detection of imminent collisions.

Academic/Industrial collaboration: Syracuse Center of Excellence on Environment and Energy Systems (sponsored by the state of NY), in the design of its fully instrumented headquarters building for situational awareness and control.

## 8. New Discoveries/Inventions/Patents

New discoveries and inventions are discussed above. No patents were filed.

## 9. Honors/Awards

During the contract period: Best Nunan Research Presentation in the EECS Department, Syracuse University, awarded to Bhagavath Kumar.

Pramod K. Varshney (PI)'s lifetime achievement awards:
Appointed Distinguished Professor, Syracuse University (2007);
Appointed Director, CASE (Center for Advanced Systems and Engineering), Syracuse University (2009).

Chilukuri K. Mohan (Co-PI)'s lifetime achievement awards:
Appointed Department Chair, the Electrical Engineering and Computer Science Department, Syracuse University (2009).